Tunable Dual-Wavelength Picosecond Pulse Generation by the Use of Two Fabry–Pérot Laser Diodes in an External Injection Seeding Scheme

M. Zhang, D. N. Wang, H. Li, W. Jin, and M. S. Demokan

***Abstract*—An attractive alternative to generate tunable dual-wavelength pulses by external injection seeding of a gain-switched Fabry–Pérot laser diode (FP-LD) is demonstrated. The external-injection-seeding branch consists of only a FP-LD, a 3-dB coupler and two fiber Bragg gratings (FBGs). The two wavelengths can be selected and their spacing can be tuned by adjusting two FBGs. The output sidemode-suppression-ratio is better than 17 dB over a 10-nm wavelength tuning range. The whole system is simple and of low cost.**

***Index Terms*—External injection seeding, gain switching, picosecond pulse.**

I. Introduction

TUNABLE multiwavelength ultrashort pulse sources around 1.55 μm are vitally important for the development of optical time-division-multiplexing (TDM) and wavelength-division-multiplexing (WDM) systems. A number of approaches have been explored in the dual-wavelength picosecond pulse generation. Schlager *et al.* demonstrated a dual wavelength pulse generation by the use of the birefringent polarization-maintaining fiber in the mode-locked erbium-doped fiber ring laser's cavity [1]. An actively mode-locked laser-diode array with a V-shaped double-stripe mirror in the external grating-loaded cavity has also been used for the dual wavelength operation by Wang *et al.* [2]. Margalit *et al.* obtained the dual wavelength pulses in an erbium-doped fiber laser by injection of two spectrally distinct but temporally synchronized pulse trains [3]. Recently, self-injection-seeding of a gain-switched Fabry–Pérot laser diode (FP-LD) has provided another way to achieve dual-wavelength picosecond pulse generation [4]. In self-seeding scheme, the repetition frequency or the length of the external cavity have to be adjusted to make the feedback pulses correspond to the selected wavelengths arrive at the gain switched FP-LD during the pulse buildup time [4]–[6]. No adjustment of feedback loop or repetition frequency is required in external injection seeding system, and the output wavelengths can be selected and tuned easily by adjusting the wavelengths of the injection light beam [7], [8]. However, a rather expensive continuous-wave (CW) tunable laser is commonly required. Multiwavelength operation is another important development of the ultrashort pulse generation and a simultaneous five-wavelength mode-locked laser source has been achieved by Nitta *et al.* [9].

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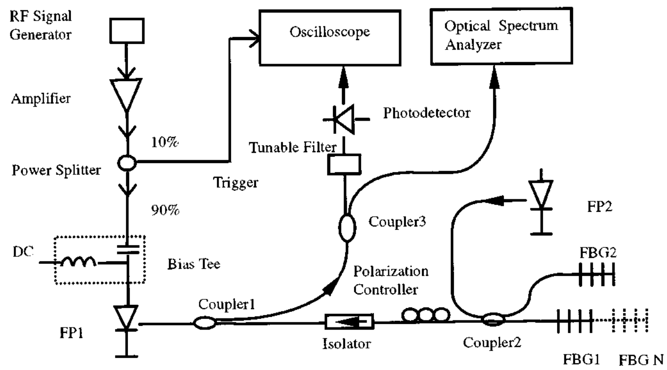

Fig. 1. Experimental setup of this work.

In this work, we present a simple external injection seeding system where only two economic FP-LDs and two FBGs are employed. The wavelength tuning range obtained is 10 nm corresponding to the sidemode-suppression-ratio (SMSR) of greater than 17 dB. A constant repetition rate of 500 MHz can be maintained during the system operation. The system can also be used for multiwavelength operation by employing more FBGs.

II. Experimental Setup

Our experimental setup is shown in Fig. 1. Two pigtailed commercially available FP laser diodes are used as the optical sources. FP1 has a peak wavelength of 1558.7 nm, a cavity mode spacing of 1.7 nm, and a threshold current of about 19.7 mA. The corresponding values for FP2 are 1554.6 nm, 1 nm and 20 mA, respectively. The spectral characteristics of FP1 and FP2 are shown in Fig. 2. The frequency linewidth of the lasing modes of FP1 at the full-width at half-maximum (FWHM) is 17.5 GHz, while the corresponding value of FP2 is 4.4 GHz. FP1 is biased at 14 mA and gain-switched at 500 MHz. FP2 is driven by the dc current. The output of FP2 is directed to a 3-dB coupler and reflected by two FBGs, both having the same Bragg wavelength of 1553.0 nm, bandwidth of 0.3 nm and reflectivity of 80%. The reflected optical waves from the FBGs are then directed to a polarization controller and an isolator. In the experiment, FP2 is used as the injection source to enable the dual wavelength operation of FP1. The wavelength of the reflected waves can be tuned by compressing or elongating the FBGs. The external injection

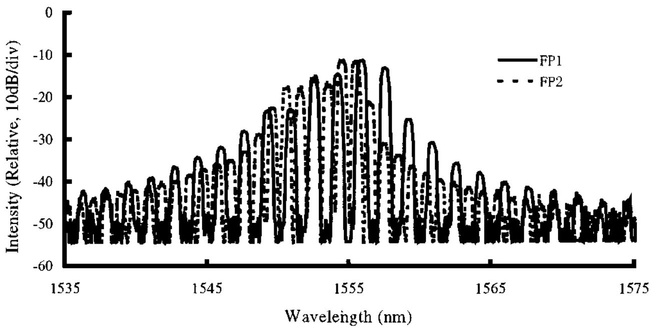

Fig. 2. Spectrum of the two laser diodes.

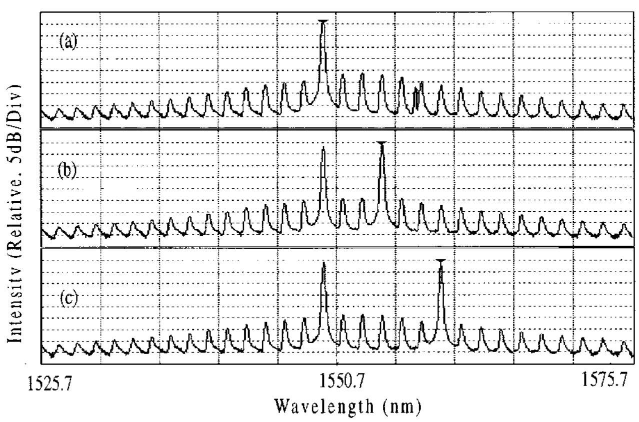

Fig. 3. Output spectra of FP1: (a) Single wavelength operation $\lambda = 1549.6$ nm; (b) Dual-wavelengths operation $\lambda_1 = 1549.6$ nm and $\lambda_2 = 1554.6$ nm; (c) Dual-wavelengths operation $\lambda_1 = 1549.6$ nm and $\lambda_2 = 1559.6$ nm.

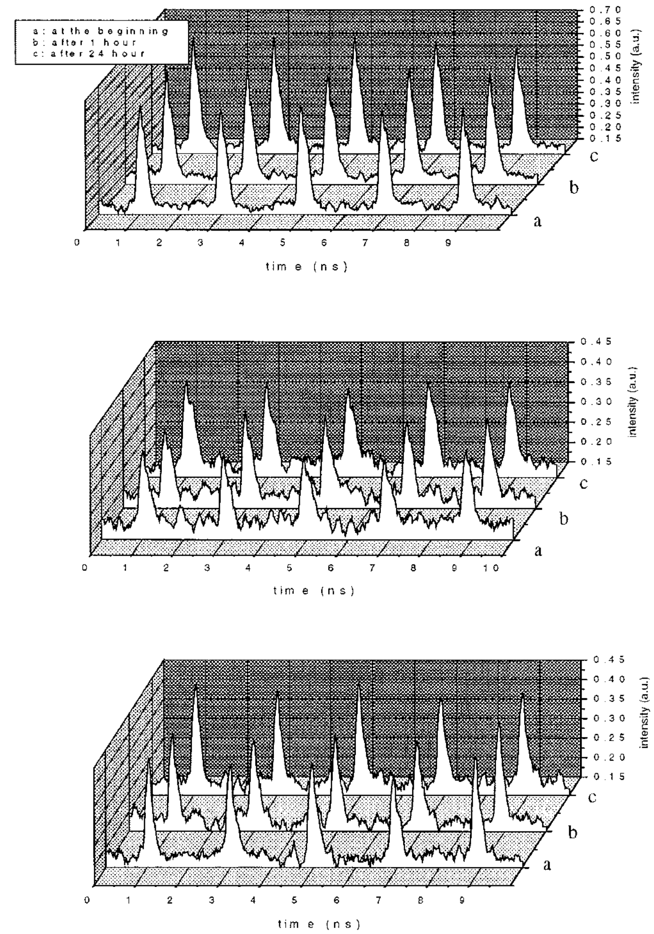

Fig. 4. Temporal profiles of the pulse trains generated at FP1: (a) the pulse trains when FP1 is in single wavelength operation at $\lambda = 1549.6$ nm; (b) the pulse trains at $\lambda_1 = 1549.6$ nm when FP1 is in dual-wavelength operation; (c) the pulse trains at $\lambda_2 = 1559.6$ nm when FP1 is in dual-wavelength operation.

seeded laser output from FP1 is then sent to a pulse detector system that consists of a tunable filter, a high-speed photodetector and a digital sampling oscilloscope. The spectral characteristics of the system output are also monitored by the use of an optical spectrum analyzer with 0.1 nm wavelength resolution.

III. Result and Discussion

The output spectra of external-injection seeded FP1 are shown in Fig. 3. When the reflected wavelength of FBG1 is tuned to close to the center of the selected mode of FP1, FP1 switches to a single-mode operation as shown in Fig. 3(a). The two wavelength outputs can be observed in Fig. 3(b) and 3(c), respectively, when the reflected wavelength of FBG1 stays at 1549.6 nm, while that of FBG2 is reflected at 1554.6 and 1559.6 nm, respectively. The polarization and wavelength of the injected light are fine tuned to maximize the SMSR. The injection power at wavelength 1549.6, 1554.6, and 1559.6 nm, respectively, is -14 dBm. It is also found that the frequency linewidth of the lasing modes of FP1 becomes about 4.4 GHz (FWHM value). The separation of the dual-wavelength peaks can be varied from 1.9 to 10 nm with the SMSR better than 17 dB. The maximum separation and the tuning range of the wavelengths are limited by the gain spectrum of the two FP-LDs. A broad gain spectrum will lead to a large tuning range.

The pulse trains, after passing through the tunable filter, can be observed by using a fast photodetector and a sampling oscilloscope as shown in Fig. 4. Fig. 4(a) shows the pulse trains when FP1 is in single wavelength operation at $\lambda = 1549.6$ nm. When FP1 is in dual-wavelength operation, the pulse trains obtained are shown in Fig. 4(b) and 4(c), respectively, after being filtered by the tunable filter. Fig. 4(b) demonstrates only the pulse trains corresponding to $\lambda_1 = 1549.6$ nm, while Fig. 4(c) shows the pulse trains of $\lambda_2 = 1559.6$ nm. It can be noticed that the pulse intensity is reduced to about a half when FP1 is in dual wavelength operation as predicted by the output spectra shown in Fig. 3. When FP1 is gain switched without external injection, the pulsewidth is about 90 ps and the average output power is 18.5 μW. When FP1 is in single-mode operation, the pulsewidth is extended to 120 ps and the average output power becomes 19.9 μW. In the case of dual-wavelength operation, the pulsewidth becomes 100 ps, and the average output power for each wavelength is about 10 μW. Fig. 4 also shows the pulse trains of each wavelength channel at different time instant during the experiment, initial time instant, 1 h later and 24 h later, respectively. The intensity of the pulse trains is stable.

The peaks of dual-wavelength can be readily selected, and their spacing and locations can be tuned easily. The results of wavelength tuning with fixed wavelength spacing are demonstrated in Fig. 5. The wavelength spacing is maintained to be 5 nm. In Fig. 5(a), the two peaks are located at 1549.6 and

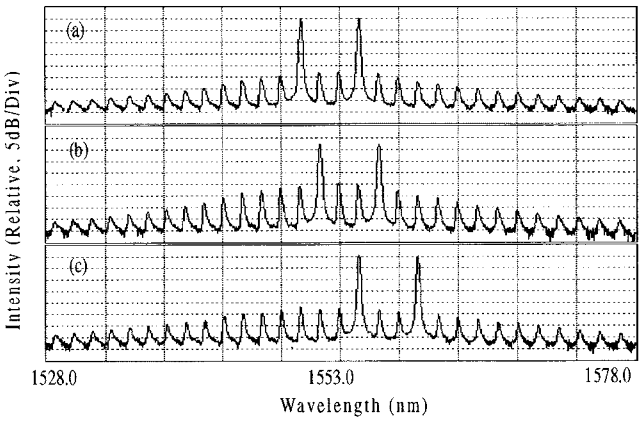

Fig. 5. Dual wavelength tuning: (a) Peak wavelengths located at 1549.6 and 1554.6 nm, respectively; (b) Peak wavelengths located at 1551.5 and 1556.4 nm, respectively; (c) Peak wavelengths located at 1554.6 and 1559.6 nm, respectively.

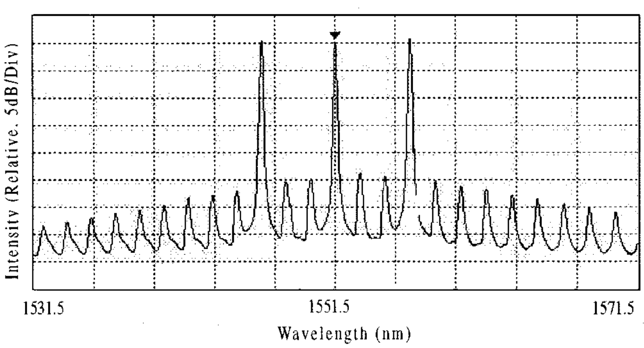

Fig. 6. Output spectra of FP1 for three wavelength operation; peak wavelengths are located at 1546.6, 1551.5, and 1556.4 nm, respectively.

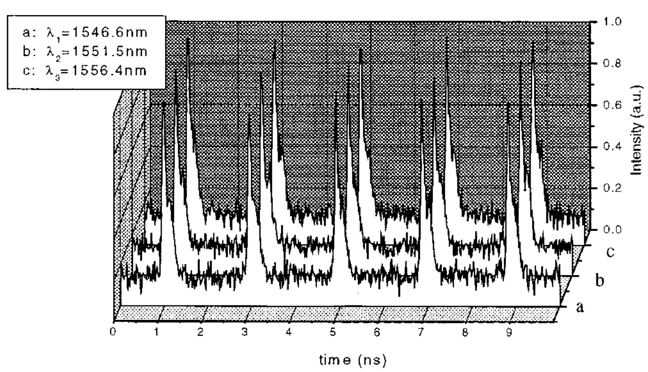

Fig. 7. Temporal profiles of the pulse trains at each wavelength channel when FP1 is in three wavelength operation $\lambda_1 = 1546.6$ nm, $\lambda_2 = 1551.5$ nm, $\lambda_3 = 1556.4$ nm.

1554.6 nm, respectively. By adjusting the two FBGs, the wavelength peaks are shifted to 1551.5 and 1556.4 nm, respectively, as shown in Fig. 5(b). A further wavelength shift can be achieved in Fig. 5(c), where the wavelength peaks are located at 1554.6 and 1559.6 nm, respectively. The value of SMSR in Fig. 5(b) is only 17 dB when compared with 23 dB in both Fig. 5(a) and 5(c). This is because the peak wavelengths of the laser modes selected from FP2 do not perfectly agree with those of FP1. However, by optimizing the dc driving condition of FP2 or employing a temperature controller for fine tuning the lasing modes of FP2, the SMSR of the output can be improved. The multiwavelength operation of the system can also be achieved by applying more FBGs in the setup. Fig. 6 shows the output spectra of FP1 when three FBGs with 90% reflectivity are employed in the setup. The peak wavelengths are located at 1546.6, 1551.5, and 1556.4 nm, respectively. Fig. 7 shows the pulse trains at each wavelength channel. Four or more wavelengths operation may also be achieved by carefully selecting two FP-LDs with the similar spectrum. In dual and multiwavelength operation, the minimum wavelength separation that can be achieved is limited by the gain competition between the selected modes. The mode spacing of FP1 is 1.7 nm, thus, when the wavelength separation is about 1.7 nm, the output wavelengths become relatively unstable and mode hopping can be observed.

IV. Conclusion

We have demonstrated a simple and efficient system to generate tunable dual-wavelength picosecond pulses. The external injection seeding branch consists of only a FP-LD, a 3-dB coupler and two FBGs. The wavelengths and their spacing can be easily selected and tuned by adjusting the FBGs while a constant repetition frequency of 500 MHz can also be maintained. By a careful laser diode selection, the wavelength tuning range and SMSR can be increased. The system is a simple and low cost alternative to the conventional dual-wavelength picosecond pulse sources.

Acknowledgment

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